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VII.

A THEORY OF THE CONSTITUTION OF THE SUN, FOUNDED UPON SPECTROSCOPIC OBSERVATIONS, ORIGINAL AND OTHER.

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FRAUNHOFER discovered the lines in the solar spectrum, known by his name, in 1814. Many efforts to determine their origin followed. One of the most ingenious and carefully considered was that of Professor Forbes in 1836.* He concluded that, if their origin is in the solar atmosphere, the light from the limb must exhibit stronger lines than that from the centre. His method was to examine the spectrum before and during an annular eclipse; as he found no recognizable change, his deduction was, "that the sun's atmosphere has nothing to do with the production of this singular phenomenon."

The point was again touched upon by Sir David Brewster and Dr. Gladstone in a joint study of the spectral lines, published in 1860.† Here "each of the authors came independently to the conclusion, that there is no perceptible difference in this respect between the light from the edge and that from the centre of the solar disk."

In 1867 Ångström ‡ repeated the experiment with negative results. Lockyer's § efforts also, in 1869, were attended with no better results.

In 1873, four years later, I devised and made an apparatus by which a perfect juxtaposition of the spectra of the centre and limb was secured. This apparatus and certain of the results gained by its use were described in a note "On a Comparison of the Spectra of the Limb and the Centre of the Sun," published in the American Journal of Science, (1873,) Vol. V. pp. 369–371. I was then a student at

* Note relative to the supposed Origin of the Deficient Rays in the Solar Spectrum. Phil. Trans., 1836, pp. 453–456.

† On the Lines of the Solar Spectrum. Phil. Trans., 1860, pp. 149–161.

‡ Phil. Mag., 1867, p. 76.

§ Proc. R. S., xvii. 350.

Yale College, and soon after left New Haven, when the research was necessarily interrupted. I hoped, however, that the novelty and interest of the observations might lead others, possessed of the necessary apparatus, to develop the results of this method of investigation. But as nothing has been published on this subject since that time, I was glad to have an opportunity to continue the investigation in the summers of 1879 and 1880. The results of my labor are embodied in this paper.

The method adopted in the recent observations is exactly the same as that described in the article cited; instead, however, of the equatorial of the Sheffield Scientific School, I used a Clark equatorial of 9.4 in. aperture and 120 in. focal length, which was kindly placed at my disposal by the gentlemen in Hartford to whom it belongs.* The New Haven spectroscope, too, of twelve effective prisms, was replaced by one of which the dispersing member was a Rutherford grating on speculum metal, either of 8,648 or 17,296 lines to the inch, at will. These gratings were of the largest size, having a ruled surface of about 1¾ in. square.

The immediate results I give in the order of the refrangibility of the lines observed, as no observed variations in them can be attributed to anything other than the temporary modifications of transparency in our atmosphere. The numbers are the places on Ångström's maps, as nearly as could be ascertained without a micrometer.

Line (C) 6561.8 is cleaner and wider at limb, i. e. the haze on either side of the line as ordinarily seen is much reduced.

6431 is slightly stronger at centre than at limb.

6371 is visible at centre, but not at limb.

(D_1) 5894.8 slightly less hazy at limb.

(D_2) 5889.0 decidedly cleaner at limb.

A fine line very close to its more refrangible side is either wanting or much fainter in spectrum of limb.

5577.5 is much stronger at limb.

5440 $\pm$ (not on Ångström's chart) is a little stronger at limb.

The Mg. lines 5183.0, 5172.0, 5166.5 (b_1 b_2 b_4) are cleaner at limb. The line b_3, belonging to a different element, does not show such a peculiarity.

5045 (a faint line not in Ångström) is stronger at limb.

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* My acknowledgments for this courtesy are gratefully accorded to Mr. Edgecomb, its former owner, and to Mr. Howard and Mr. Chapin, its present owners.

4919 ±, a faint line slightly stronger at limb.

(*F*) 4860.6 is much cleaner, more free from haze at limb.

4702.3 seems cleaner at limb.

4340.0 cleaner at limb.

4226.4 shows less haze at limb.

4101.2 is a very hazy line, so represented by Ångström, but at limb i is practically free from haze, — a striking difference.

4045 is slightly less hazy at limb.

Other differences have been recorded, but only these have been observed more than once each.

Any theory of the sun, worthy of attention, must not only explain the above-described phenomena, but also others better known, and as yet not accounted for satisfactorily. Of these the most noteworthy is the spectroscopic appearance of a spot and its penumbra. As is well known, such a spectrum exhibits a very strong general absorption, with a very slightly modified elective absorption. A few faint lines appear in the spot spectrum which are not otherwise seen; and a few faint lines of the ordinary spectrum are strengthened. A careful examination has persuaded me that the spectrum of a spot differs from that of the unbroken photosphere, just as the spectrum of the limb differs from that of the centre of the disk, save that the variations are more pronounced. Indeed, I could have considerably extended the list of lines strengthened at limb by an examination of the spot spectrum, where the variations appeal to the eye more clearly.

The accepted theory of the spots attributes the phenomenon to the absorption of the solar light by cooler, denser gases of the same nature as those producing the Fraunhofer lines. Familiar experiments teach, however, that, as the density of a gas increases, the change in the character of its radiation is shown in its spectrum by the broadening of its distinctive spectral lines, which at the same time grow more ill defined. Therefore it follows that, according to the law connecting radiation and absorption, dark lines produced by such a gas must also, under similar conditions, show increased breadth and diminished sharpness. That no such changes are to be recognized, is a fatal objection to the theory.

Another class of unexplained phenomena is the duplicity of certain lines of the solar spectrum, lines which are single in the spectra of terrestrial sources. Of these Professor Young has discovered E_1, b_3, and b_4, with others.

My own observations can be arranged very simply in classes, and will then better lend themselves to theoretical discussion.

I. The most important fact of all is that the differences in the two spectra of centre and limb are extremely minute, escaping all but the most perfect instruments, and all methods which do not place them in close juxtaposition.

II. Certain lines, the thickest and darkest in the spectrum, notably those of hydrogen, magnesium, and sodium, which appear with haze on either side, in the spectrum of the centre of the solar disk, are deprived of this accompaniment in that of the limb.

III. Certain very fine lines (four observed) are stronger at limb.

IV. Other very fine lines (two or three observed) are stronger at centre.

The ordinarily accepted theory of the origin of the Fraunhofer lines fails to explain the phenomena as observed. That is, if we suppose the photosphere, whether solid, liquid, gaseous, or cloud-like, to yield a continuous spectrum which is modified only by the selective absorption of a surrounding atmosphere, then the absorption must be greater at the limb than at the centre of the solar disk; and this must be true independently of the thickness of that atmosphere, as well as of the form, rough or otherwise, of the surface of the photosphere. This evident consequence, pointed out in the first place by Forbes, nearly half a century ago, cannot be avoided. There is but one way of maintaining the theory and escaping Forbes's conclusion already quoted, and that the course pursued by Kirchhoff in the original statement of his theory of the solar constitution,* namely, by assuming that the depth of the reversing atmosphere is not small compared to the radius of the sun. But innumerable observations during the score of years which have lapsed since that time prove that such a reversing atmosphere must be very thin. The famous observation of Professor Young during the total eclipse of 1870, when he saw appreciably all the Fraunhofer lines reversed, has naturally been received as the strongest confirmation of Kirchhoff's views as to the locus of the origin of the dark lines. But this very observation restricts the effective atmosphere (save for hydrogen and one or two other substances) to a depth of not more than 2″. Thus, singularly enough, the very observation which led to the firmest belief among spectroscopists in the correctness of Kirchhoff's view exposed, at the same time, its most vulnerable point.

Another theory of the solar constitution, that of Faye, assigns a different seat to the stratum producing the Fraunhofer lines, namely,

* Untersuchungen über das Sonnenspectrum, (Berlin, 1862,) pp. 14, 15.

the photosphere itself. Regarding the principal radiation of the sun as coming from solid or liquid particles floating in a gaseous medium, the cloud-like stratum thus formed is necessarily somewhat transparent. According to his views, these particles are the sources of the continuous spectrum, and the medium in which they float is the locus of the selective absorption.* Thus he attempts to reconcile the general theory of Kirchhoff with the observations and deductions of Forbes, which, as we have seen, were a constant stumbling-block in the way of accepting Kirchhoff's explanation.

Lockyer seems to have accepted this theory, and to have defended it in the earlier portion of his work; † but in 1872, after Young's important observation of 1870 and its confirmation in 1871, he changed his views, and regarded the layer just outside the photosphere as the true seat of the selective absorption producing the Fraunhofer lines.‡ I supposed in 1873 that my observations then published could be explained on Faye's hypothesis.

There is, however, a fatal objection to the explanation as given by this theory. If the luminous particles are precipitated from the vapors of the photosphere, they cannot be at a higher temperature than the circumambient gases; on the contrary, on account of their greater radiating power, they must be slightly cooler. But the fundamental theory of absorption demands a lower temperature for the vapor producing dark lines than that of the principal source of light behind it; consequently this view of Faye cannot be accepted without great modifications.

Before advancing any theory of my own, it may be well to emphasize two principles taught by the theory of absorption, to which all hypotheses must be conformable. That Faye's fails in this is sufficient cause for its rejection.

1. To produce dark lines in a spectrum by absorption, the source of absorbed light *must* be at a higher temperature than that of the absorbing medium.

2. There is an inferior limit of brightness, below which the source of absorbed light cannot go without the spectral lines becoming bright.

Of these, the first is familiar, and requires here neither proof nor

* Comptes Rendus, lx., 1865.

† See "A Lecture delivered at the Royal Institution," May 28, 1869, quoted in Lockyer's Solar Physics, pp. 220, 221; also "The Rede Lecture," May 24, 1871, quoted in Solar Physics, pp. 317, 318.

‡ See revised report of two lectures delivered at Newcastle-upon-Tyne in October, 1872, Solar Physics, p. 409.

comment; the second, though not less evident, is less familiar because less important. As we shall make use of it, however, it may be well to enforce it by reference to common experience. Were it not true, it would be impossible to see bright lines in the spectrum of any flame to which daylight had access, for in this case the conditions demanded by the first principle are fully met, the sun being the origin of the daylight. That we do not see absorption lines is due then alone to the lack of necessary brilliancy in the daylight.

Thus much premised, we can frame a theory which explains all the observed phenomena exhibited by the spectroscope, and is also rendered highly probable by the revelations of the telescope.

As is well known, the solar surface, when examined with a powerful telescope of large aperture, presents a granulated appearance, the granules in general subtending an angle of a fraction of a second only. Probably this appearance is better known to the majority of astronomers by means of Professor Langley's admirable drawings,* rather than by personal observation. These granules I regard as marking the locus of currents directed generally from the centre of the sun. About these currents are necessarily currents in an opposite direction, which serve to maintain a general equilibrium in the distribution of mass. Let us consider the action of such an ascending current. Starting from a low level at a temperature which we may regard as above the vaporizing point of all elements contained in it, as it rises to higher levels, it cools, partly by radiation, more by expansion, until finally the temperature falls to the boiling point of one or more of the substances present. Here such substances are precipitated in the form of a cloud of fine particles, which are carried on suspended in the current. The change of state marked by the precipitation is accompanied by a sudden increase in radiating power; hence these particles rapidly lose a portion of their heat, and become relatively dark, to remain so until they are returned to lower levels by the currents in a reverse direction.

In this theory, it will be observed, there is nothing which does violence to our accepted notions of the solar constitution. Indeed, it differs chiefly from that of Faye in localizing the phenomena of precipitation, instead of regarding it as proper to all portions of the photosphere; and, what is quite as important, in supposing the precipitation confined to one or two elements only. I shall attempt to define these elements farther on.

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* Am. Jour. Sci., Vol. VII., 1874, and Vol. IX., 1875, Plates.

In our theory, then, the granules are those portions of upward currents where precipitation is most active, while the darker portions, between these bodies, are where the cooler products of this change with accompanying vapors are sinking to lower levels.

Having stated the theory, we will now apply it to the four classes of phenomena defined above.

From the nature of the condensation the granules or cloudy masses must be very transparent, because the condensation is confined to elements which have very high boiling-points, and because such elements can be but a portion, perhaps but a small portion, of the whole matter contained in the upward currents. It is not *a priori* improbable that we receive light from many hundreds of miles below the general outer surface of the photosphere. Since these cloud-like sources of intenser radiations are surrounded on all sides by descending currents of colder vapors, *all* the white light which comes to us must have passed through media capable of modifying it by selective absorption. Again, since at the centre of the solar disk we can see as far into the photosphere as at the limb, and practically no farther, the phenomena of absorption ought to be, on the whole, the same in both regions.

Thus the fundamental and most important class of phenomena above classified finds a simple and logical explanation.

With regard to the phenomena of Class II. we have but to define the problem in order to find the solution at hand. All the lines of Class II. belong to vapors which lie high in the solar atmosphere, as is evident from their frequent reversal in the chromosphere. On the centre of the disk these lines are hazy or "winged," but not so at the limb. To the spectroscopist this aspect is characteristic of greater pressure, that is, of more frequent molecular impact. The observation then proves that the dark lines of hydrogen, magnesium, sodium, etc., as seen at the centre of the solar disk, are produced by the elements in question at a higher pressure than the corresponding lines at the limb. Accepting our theory, this must be so; for, supposing the transparency of the photosphere is such that we can see into it a distance of 2,000 miles, then at the centre of the disk we have light modified by selective absorption all the way from the extreme outer chromosphere down to 2,000 miles below the upper level of the photosphere; while 10″ from the limb the light, though coming from the same depth of vapor measured along the line of vision, has its lowest origin more than 1,700 miles farther from the sun's centre than in the previous case. Of course the numbers here used have no definite significance,

but, modify them as we will, within the bounds of probability, the reasoning remains the same.

Suppose now a certain vapor which is confined to the upper stratum of the photosphere, or, rather, one of which the lower limit is thus restricted; then, according to the reasoning of Forbes, the force of which has been shown, its absorption lines ought to be strongest at the limb. This is the condition which produces the phenomena of Class III.

Before discussing the final class, we must recall a fact familiar to the most casual observer of the sun, namely, that lying upon the photosphere is a stratum producing a very strong general absorption, so strong indeed that the disk is probably less than a fourth as brilliant near the edge as at the centre. This layer is *very thin*, as proved by the great difference in brilliancy between the upper and lower portions of faculæ.

Since the difference of absorption at the two levels is very great, the conclusion follows, because the facula itself is so low that it rarely, if ever, appears as a projection on the limb of the sun. For convenience let us call this layer A.

Imagine then, a stratum of vapors, B, above the layer just described, which are not represented at all in the photosphere, and which are of nearly the same temperature as this layer A.* Then (for the sake of simplicity regarding this layer as having no elective absorption) suppose all beneath the two spherical shells in consideration to be removed. In the spectroscope, light from such a source as the two layers A and B would yield a continuous spectrum; for the inner shell (A), radiating only white light, would be robbed of nothing not supplied in equal quantity by radiation from the outer shell (B), since they are of the same temperature. If such layers as these really do exist about the sun, we can now readily state the appearances which would be presented by a sun so constituted, if the threefold system should be studied spectroscopically. In the centre of the projected disk, the lines proper to the exterior shell (B) would be

* This supposition is not opposed to probability, for though we must regard the temperature as generally decreasing in passing from the photosphere outward, it does not follow that this decrease is continuous. A similar general law may be stated for our own atmosphere, but in a clear night the air in the immediate vicinity of the ground is colder than that just above. The explanation of this phenomenon is familiar in the theory of dew and hoar-frost. Analogous causes for irregularity in the distribution of temperature in the solar atmosphere must be even more efficacious, since the layer A is probably a more vigorous radiator than the earth, and the gases above it are certainly far more diathermous than our atmosphere.

reversed, i. e. dark. As we approached the edge, however, *owing to the opacity of the inner shell*, the conditions would approximate to what they would be if the layers A and B existed alone, the central body being removed, and the lines would fade; if faint, they would vanish. This is our explanation of the phenomena of Class IV.

Every theory involves certain conditions. We finally judge of the soundness or unsoundness of any theory largely from the consideration of these implied conditions, and of the extent to which they are fulfilled by it. For instance, our explanation of the fact that certain very fine lines are stronger at the centre (IV.) demands that the substances giving such lines should be found in the chromosphere, indeed mainly restricted to the chromosphere. Fortunately I can say that one of them (6371), which I first discovered and measured carefully, is identical with the fourteenth line of Young's second Catalogue of Chromosphere Lines. The other one, the wave-length of which I took from Ångström's chart without correction, may correspond with Young's ninth (6429.9) line of the same Catalogue, which differs in place by only one sixth the distance between the *D* lines. This I shall test at the earliest opportunity.

If the theory I have proposed is correct, it affords the first definite evidence of the existence of *chemical compounds* in the sun, for in accordance with it the lines of Class III. and Class IV. belong to substances which are not found in the lower photosphere. We know however that all gases must increase in density in passing from their outer limit towards the centre of the sun; and we have seen a proof of this in the case of hydrogen and certain other vapors in the discussion of our observations, which showed that the characteristic lines indicated greater density when they originated at greater depths. The only escape from the contradiction is in the assumption that the lines of the last two cases (III., IV.) are due to compound vapors having a dissociation temperature below that of the lower photosphere. Of course, the substances of Class IV. have a lower dissociation temperature than those of Class III.

A naturally suggested and legitimate subject of speculation is as to the nature of the substance which, by precipitation, forms the cloud-masses of the photosphere. We may predicate three properties with greater or less positiveness, viz.: —

1st. The substance has a boiling-point above that of iron, for iron vapor at a lower temperature exists in the immediate neighborhood.

2d. The molecular weight is probably not great; for, though precipitated below the upper natural limit of its vapor, there are few ele-

ments found in abundance above it, and those in general of low vapor density.

3d. The element is not a rare one. Of these guides the last is perhaps of the least value.

The substances which apparently meet all these conditions are carbon and silicon: nor is it easy to name any other which will. Accepting for a moment as an hypothesis that the light coming from the sun is radiated by solid or liquid particles of carbon just at the point of vaporization, let us see if the facts of observation fulfil the implied conditions.

As a first consequence, we see that the temperature and light of the photosphere are defined as those of solid carbon at the point of volatilization. In the electric arc there is a very small area of the positive carbon pole at this high temperature. Though this area is in a very disadvantageous position for observation, and can consequently have but a disproportionately small share in producing the total effect, the splendor of the electric light might almost tempt us to believe the guess a valid one. Another consequence implied, however, — namely, that the spectral lines proper to simple carbon are absent in the solar spectrum, — is doubtless better adapted as a crucial test of the hypothesis than a study of the electric light. There has been evidence recently offered that carbon lines are present in the solar spectrum. Granting this, we perceive that the photosphere contains solid or liquid particles hotter than carbon vapor, and consequently not carbon.

I am then inclined to suspect that the photospheric material may be silicon, which, though denser in the gaseous state than carbon, is not improbably more abundant. There is also good reason to suppose that carbon is precipitated at a higher level; and the analogous but less common element boron may add a minor effect.

In the explanations which I shall give of the remaining phenomena, it may serve to fix the ideas, to think of the granules which characterize the sun's photosphere as clouds of a substance like precipitated silicon. At any rate, we are sure that the substance in question, so far as we know it, has properties similar to those of the carbon group.

I have given plausible explanations of all the phenomena included specially in my own observations. It remains to discuss the others, briefly mentioned above.

The substance precipitated cools very rapidly, as it is an excellent radiator separated from space only by extremely diathermous media. It forms then a smoke-like envelope, which ought to exert just such a general absorption as that observed at the limb of the sun. It is thin

because of the relatively great density of the substance in the liquid or solid state; thus the apparent brilliancy of the faculæ is readily understood.

If there is any disturbing cause which would tend to direct currents of gas, over a considerable area of the solar surface, toward a point, this smoke, instead of quietly settling down to lower levels between the granules, would concentrate about this point, there exercising a marked general absorption which would betray itself as a spot. At this place the suspended particles would sink to lower levels with constantly increasing temperature, until finally, heated to intense incandescence, they would revolatilize. Thus the floor or substratum of every spot must be a portion, depressed it is true, of the photosphere. All the spectroscopic phenomena of spots, which have proved so perplexing, are thus naturally and easily explained.

In the immediate neighborhood of a spot, the centripetal currents bend down the ordinary convection or granule-producing currents, so that they are approximately level. Before, the latter cooled suddenly by rarefaction in their upward course; now, they cool mainly by the much slower process of radiation; thus, while before the locus of precipitation was restricted, it is now greatly extended. This is the cause of the great elongation of the granules in the penumbra, — a real elongation, I imagine, and not merely an apparent one.

Finally, concerning the close duplicity of certain lines, we may reason thus: — If we could surround the sun by a stratum of gas hotter than the photosphere and much rarer than that producing the corresponding Fraunhofer lines, we should, as is shown by a course of reasoning which I have given in another place,* see each dark line divided by a sharp bright line in its centre, that is, doubled. But as a consequence of the theory this supposed condition must be practically met in the case of certain vapors in the sun. The gases just over the granules, in the vertical currents, are at a very high temperature, essentially that of the condensing material itself, consequently much hotter and rarer than the relatively low-lying vapors which, as we have seen, produce the Fraunhofer lines.

There are, however, certain evident limitations to these conditions; in other words, we cannot expect to see all the dark lines doubled by any increase of dispersive power. For instance, a line must have a marked tendency to broaden with increased pressure, otherwise the duplication cannot be pronounced. Again, the layer of rare vapor must

* On Lockyer's Hypothesis. Am. Jour. Chem., i. 15.

be thin, or its temperature cannot be relatively high throughout, as demanded by the theory. This evident condition doubtless gives the reason why the hydrogen lines, though the broadest in the solar spectrum, are not sensibly double.

The theory of the constitution of the sun above proposed may be briefly recapitulated thus: —

Convection currents, directed generally from the centre of the sun, start from a lower level, where the temperature is probably above the vaporizing temperature of every substance. As these currents move upward they are cooled, mainly by expansion, until a certain element (probably of the carbon group) is precipitated. This precipitation, restricted from the nature of the action, forms the well-known granules. There is nothing which has come under my observation which would indicate a columnar form in these granules under ordinary circumstances.

The precipitated material rapidly cools, on account of its great radiating power, and forms a fog or smoke, which settles slowly through the spaces between the granules till revolatilized below. It is this smoke which produces the general absorption at the limb, and the "rice-grain" structure of the photosphere.

When any disturbance tends to increase a downward convection current, there is a rush of vapors at the outer surface of the photosphere toward this point. These horizontal currents, or winds, carry with them the cooled products of precipitation, which, accumulating above, dissolves slowly below in sinking. This body of smoke forms the solar spot.

The upward convection currents in the region of the spots are bent horizontally by the centripetal winds. Yielding their heat now by the relatively slow process of radiation, the loci of precipitation are much elongated, thus giving the region immediately surrounding a spot the characteristic radial structure of the penumbra.

This conception of the nature of the penumbra implies a ready interpretation of a remarkable phenomenon, amply attested by the most skilful observers, and, as far as my knowledge goes, wholly unexplained; namely, the brightening of the inner edge of the penumbra in every well-developed spot.*

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* Relating to this phenomenon we see important observations by Professor Langley, Am. Jour. Sci., Vol. IX. (1875,) p. 194; also Le Soleil, par Le P. A. Secchi, Paris, 1875, Chap. IV. p. 81, and particularly Fig. 46, p. 90, with explanatory text.

This interpretation is perhaps most readily imparted by a comparison of the hot convection currents in the two cases. When the convection current is rising vertically, the medium is cooled by expansion until the precipitation temperature is reached, when all the condensible material appears *suddenly*, save as it is somewhat retarded by the heat liberated in the act. Immediately afterward the particles become relatively dark by radiation. In the horizontal currents a very different condition of things obtains. Here the medium does not cool dynamically by expansion, but only by radiation; hence, since the radiation of the solid particles is enormously greater than that of the supporting gas, practically by that of the particles themselves. Thus after the first particle appears, it must remain at its brightest incandescence until all the material of which it is composed is precipitated. From this we see that such a horizontal current must increase gradually in brilliancy to its maximum, and then suddenly diminish, — an exact accordance with the facts as observed.

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September, 1880.